Static and dynamic magnetic properties of epitaxial $Fe_{1.7}Ge$ thin films grown on Ge(111)

M. Belmeguenai, D. Berling, G. Garreau, S. M. Chérif, D. Faurie, W. Seiler, and P. Moch

Citation: Journal of Applied Physics **111**, 07D502 (2012); doi: 10.1063/1.3672396
View online: https://doi.org/10.1063/1.3672396
View Table of Contents: http://aip.scitation.org/toc/jap/111/7
Published by the American Institute of Physics

Static and dynamic magnetic properties of epitaxial $Fe_{1.7}Ge$ thin films grown on Ge(111)

M. Belmeguenai,[1,a)] D. Berling,[2] G. Garreau,[2] S. M. Chérif,[1] D. Faurie,[1] W. Seiler,[3] and P. Moch[1]
[1]*LSPM, CNRS-UPR 3407, Université Paris 13, 99 avenue Jean-Baptiste Clément, 93430 Villetaneuse, France*
[2]*IS2M, CNRS-LRC 7228, Université de Haute-Alsace, 4 rue des frères Lumière, 68093 Mulhouse Cedex, France*
[3]*PIMM, ENSAM, 151 Boulevard de l'Hôpital, 75013 Paris, France*

(Presented 1 November 2011; received 19 September 2011; accepted 25 October 2011; published online 23 February 2012)

We have studied the magnetic properties of thin epitaxial hexagonal $Fe_{1.7}Ge$ films grown on Ge(111) substrates by molecular beam epitaxy. For all samples, X-ray diffraction revealed an excellent epitaxy of the $Fe_{1.7}Ge$ films, with crystallographic $[11\bar{2}0]$ and $[1\bar{1}00]$ axes lying in the sample plane. The static magnetic properties were studied by Magneto-Optical Kerr Effect (MOKE) at room temperature. The dynamic magnetic properties at room temperature were investigated by Micro-Strip Ferromagnetic Resonance (MS-FMR). The frequency dependence of the spectra versus the orientation of the applied in-plane magnetic field shows that the contribution of the in-plane anisotropy to the magnetic energy density consists in two distinct terms exhibiting a twofold and a sixfold symmetry, respectively. The amplitude of the sixfold anisotropy constant is an increasing function of the film thickness. The observed angular dependence of the MOKE reduced remanent magnetization is described using a coherent rotation model. A good agreement is observed between the in-plane anisotropy values derived from MS-FMR and those obtained with MOKE Transverse Bias Initial Inverse Susceptibility and Torque data. [doi:10.1063/1.3672396]

I. INTRODUCTION

The realization of materials that combine semiconducting behavior with robust magnetism is a big challenge for researchers. These ferromagnetic semiconductors (FS)[1] are promising for future spintronics devices taking advantage of the long spin lifetime in semiconductors since the spin can be used as an information carrier, and of their compatibility with existing complementary metal oxide semiconductor technologies. Unfortunately, the different FS compounds investigated until now have Curie temperature significantly below room temperature.[2] FS alloys obtained from ferromagnetic transition metals and IV-semiconductors such as FeGe are expected to provide a promising solution.

Recently, FeGe thin films (thickness below 10 nm) of various stochiometries with a ferromagnetic/semiconductor interface exhibiting a high thermal stability, have been successfully epitaxially grown on Ge(111).[3,4] The authors showed that these films adopt the hexagonal $B8_2$ structure and that the Curie temperature depends on the stoichiometry and rises up to 450 K for composition close to Fe_2Ge. However, these studies were mainly focused on structural properties and on some partial static magnetic properties.

In this paper we investigate the structural and the static as well as the dynamic magnetic properties of $Fe_{1.7}Ge$ thin films grown on a Ge(111) wafer, in order to exhibit correlations between their structure, their thickness and their magnetic anisotropies. For this purpose, studies of ferromagnetic resonance in microstrip line (MS-FMR) under an in-plane applied magnetic field, of combined transverse biased initial inverse susceptibility and torque (TBIIST) and of Magneto-Optical Kerr Effect (MOKE) were performed. The MS-FMR technique provides information about various important properties, such as the effective magnetization and the effective magnetic anisotropy fields.

II. SAMPLES AND EXPERIMENTAL SET-UPS

The 6, 10 and 31 nm-thick $Fe_{1.7}Ge$ films were deposited on Ge(111) wafers by molecular beam epitaxy using Fe and Ge thermal evaporators. Fe and Ge were co-evaporated at room temperature. The thickness was determined with a quartz microbalance. The epitaxy was controlled by X-ray diffraction using a four circles diffractometer in Bragg-Brentano geometry and a monochromatic Cu source. The epitaxial relations between $Fe_{1.7}Ge$ and Ge write as $[0001]_{FeGe}//[111]_{Ge}$ in the out-of-plane direction, as $[11\bar{2}0]_{FeGe}//[1\bar{1}0]_{Ge}$ and $[1\bar{1}00]_{FeGe}//[11\bar{2}]_{Ge}$ in the sample plane. The out-of-plane lattice parameter c, deduced from the $\theta-2\theta$ spectra, is equal to 4.97 Å, in good agreement with the previously published value.[4] We performed Φ-scans related to the $(0\bar{1}11)_{FeGe}$ crystallographic family: the appropriate value of the declination angle Ψ between the scattering vector and the normal to the film (c axis) was found equal to 53°: it corresponds to $c/a = 1.25$ (where a is the in-plane lattice parameter), as expected from the results concerning macroscopic ingots.[5] The intensity variations versus the rotational angle Φ are shown on Fig. 1: the six equidistant peaks, observed in the three samples, are characteristic of the epitaxial growth of a film of hexagonal symmetry.

a)Author to whom correspondence should be addressed. Electronic mail: belmeguenai.mohamed@univ-paris13.fr.

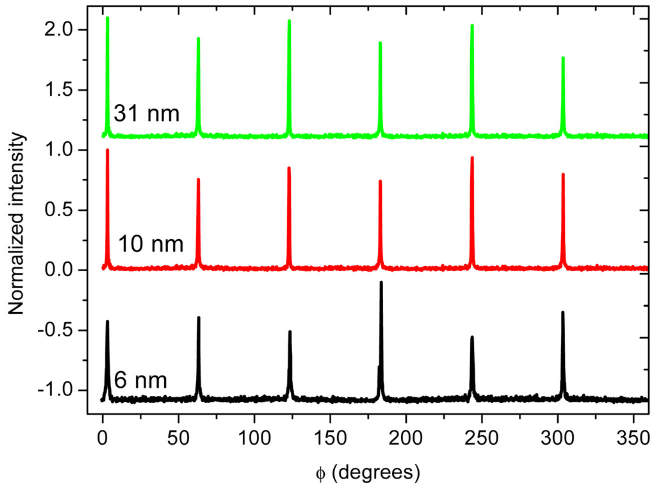

FIG. 1. (Color online) Angular variations of the X-ray intensity (Φ-scans) for different $Fe_{1.7}Ge$ thin films. Graphs are shifted vertically with respect to that of the 10-nm-thick sample for clearness.

III. MAGNETIC PROPERTIES

A. Static magnetic measurements

The room temperature hysteresis loops with an in-plane applied magnetic field along various orientations (φ_H is the in-plane angle between the magnetic applied field H and the $[11\bar{2}0]_{FeGe}$ axis) were studied by MOKE measurements in longitudinal geometry for all the samples in order to derive their magnetic anisotropy properties. The results are illustrated in Fig. 2 for the 10-nm-thick sample. One observes differences in shape of the normalized hysteresis loops depending on the field orientation. The shape along the $[11\bar{2}0]_{FeGe}$ axis (φ_H=0°) roughly corresponds to hard axis behavior: it shows a reduced remanent magnetization (M_r/M_s) of 0.22, a coercive field of about 5 Oe and a saturation field of 60 Oe. For a field applied perpendicular to $[11\bar{2}0]_{FeGe}$, the hysteresis loops have a rectangular shape with a remanence coefficient close to 1. As φ_H increases systematically away from the $[11\bar{2}0]_{FeGe}$ axis direction, the coercivity increases and the hysteresis loops tend to have an easy axis shape. The φ_H dependence of M_r/M_s is illustrated in Fig. 3(a): it looks dominated by an uniaxial in-plane anisotropy contribution. The coercive field along the easy axis is sample dependent but is not clearly related to thickness. Complementary conventional magnetization measurements should be done in order to provide a precise estimation of the magnetization at saturation for anisotropies analysis.

In addition, a quantitative evaluation of the in-plane magnetic anisotropy parameters is obtained by means of the TBIIST technique.[6] The experimental details are not described in the following, but obtained resulting values are given in Table I in view of comparison with the results of the following dynamic study.

B. Dynamic magnetic properties

The dynamic magnetic properties were investigated using a previously described MS-FMR[7] setup. We assume a magnetic energy density which, in addition to Zeeman, demagnetizing and exchange terms, is characterized by the following anisotropy contribution:

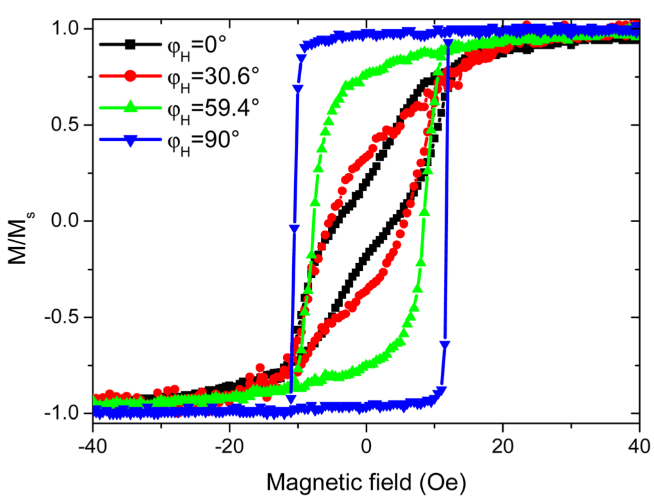

FIG. 2. (Color online) MOKE magnetization loops of the 10-nm-thick $Fe_{1.7}Ge$ film. The magnetic field is applied parallel to the film surface, at various angles (φ_H) with the $[11\bar{2}0]_{FeGe}$ axis.

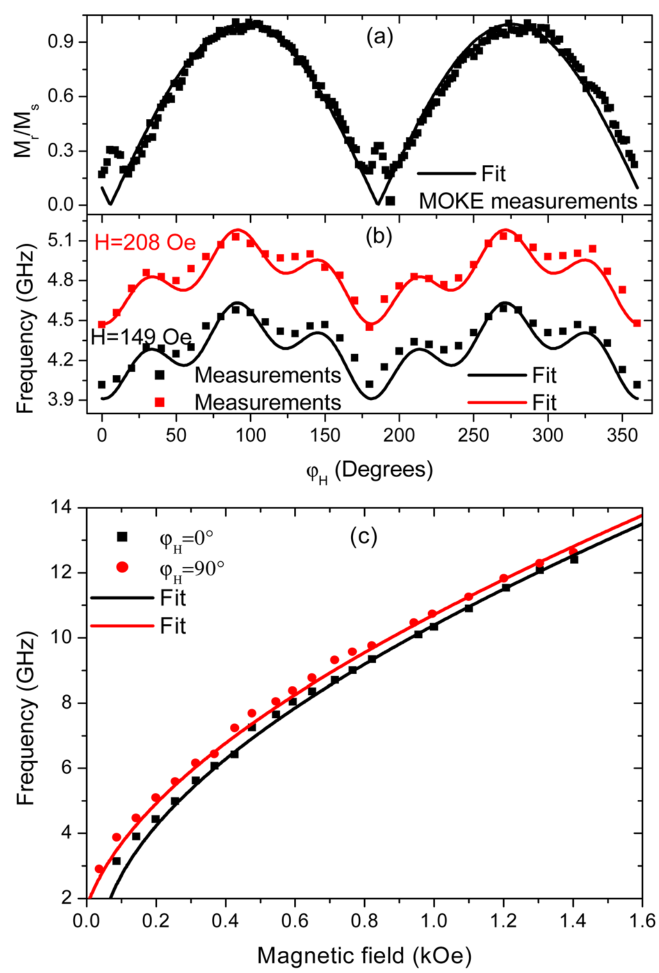

FIG. 3. (Color online) The 10 nm-thick $Fe_{1.7}Ge$ film: (a) MOKE reduced remanent magnetization (M_r/M_s), (b) in-plane angular dependence of the resonance frequency and (c) in-plane field dependence of the frequency of uniform precession mode. All the fits (full lines) are obtained using the parameters indicated in the Table I.

TABLE I. Magnetic parameters (effective magnetization $4\pi M_{\mathrm{eff}}$, uniaxial in-plane anisotropy field H_u, uniaxial easy magnetic axis angle φ_u, the sixfold in-plane anisotropy field H_6 and six order easy magnetic axis angle φ_6) obtained from MS-FMR and TBIIST measurements for the various $Fe_{1.7}Ge$ thin films.

	$4\pi M_{\mathrm{eff}}$ (kOe)	$H_6=6K_6/M_s$ (Oe)		$H_u=2K_u/M_s$ (Oe)		φ_6 (°)		φ_u (°)	
d (nm)	MS-FMR	MS-FMR	TBIIST	MS-FMR	TBIIST	MS-FMR	TBIIST	MS-FMR	TBIIST
6	11.5	105	96	5.5	6	30	30	156	159
10	12.7	220	192	19	16.5	30	31	99	101
31	13.4	900	830	10	9.2	30	33	90	82

$$
\begin{aligned}
E = & -M_s H[\sin\theta_M \sin\theta_H \cos(\varphi_M-\varphi_H)+\cos\theta_M\cos\theta_H] \\
& -(2\pi M_s^2 - K_\perp)\sin^2\theta_M - \frac{1}{2}(1+\cos2(\varphi_M-\varphi_u))K_u\sin^2\theta_M \\
& +\frac{K_6}{108}\begin{bmatrix} -2\cos^3\theta_M + 3\cos\theta_M\sin^2\theta_M + \\ \sqrt{2}(1+2\cos2(\varphi_M-\varphi_6))\sin^3\theta_M\sin(\varphi_M-\varphi_6) \end{bmatrix}^2 .
\end{aligned} \tag{1}
$$

In the above expression, θ_M and φ_M, respectively, represent the out-of-plane angle and the in-plane (referring to the $[11\bar{2}0]_{\mathrm{FeGe}}$ axis) one which define the direction of the magnetization $\boldsymbol{M_s}$; φ_u and φ_6 stand for the angles of the easy uniaxial axis and of the easy sixfold axis, respectively, with this axis. In addition, K_u and K_6 are chosen positive. It is convenient to introduce the effective magnetization $4\pi M_{\mathrm{eff}} = 4\pi M_s - 2K_\perp/M_s$, the uniaxial in-plane anisotropy field $H_u = 2K_u/M_s$ and the sixfold in-plane anisotropy field $H_6 = 6K_6/M_s$.

The resonance frequency F_r of the uniform precession mode can be obtained from the energy density as follows:

$$
F_r^2 = \left(\frac{\gamma}{2\pi}\right)^2 \frac{1}{M_s^2\sin^2\theta_M}\left[\frac{\partial^2 E}{\partial\theta_M^2}\frac{\partial^2 E}{\partial\varphi_M^2} - \left(\frac{\partial^2 E}{\partial\theta_M\partial\varphi_M}\right)^2\right], \tag{2}
$$

where the terms of Eq. (2) are evaluated at equilibrium and where γ is the gyromagnetic factor related to the effective g-Landé coefficient (we supposed $g \approx 2$ in our fit).

Figure 3(b) illustrates the experimental in-plane angular-dependence of F_r in the 10 nm-thick film, compared to the best obtained fits using Eq. (2). For all the samples, the obtained values of the magnetic parameters corresponding to these fits are reported in Table I.

In all the investigated films the easy axis of the sixfold magnetic anisotropy lies at 30° ($\varphi_6 = 30°$) of the $[11\bar{2}]$ axis of the substrate. The sixfold magnetocrystalline anisotropy field increases with the thickness. Note that the twofold anisotropy easy direction is sample dependent, with a field Hu rather small and uncorrelated neither to the thickness nor the crystallographic directions. The exact origin of this uniaxial term remains under discussion: the observed dispersion of the direction and of the amplitude of $\boldsymbol{H_u}$ are presumably related to small uncontrolled miscuts and/or to sample roughness due to the oblique flux evaporation giving rise to variable interfacial strains providing additional anisotropic contributions to magnetic energy density. The stoichiometry variations which are estimated to 10% can also affect the anisotropy. It is worth to mention that $4\pi M_{\mathrm{eff}}$ substantially increases with thickness. As mentioned above, magnetization measurements should be done to identify whether this increase is due the decrease of the interfacial strain through the magneto-elastic coupling or to the increase of the magnetization at saturation. As illustrated in Table I there is a good agreement between the in-plane anisotropy values derived from MS-FMR and from TBIIST data.

Finally, it appears that the set of in-plane magnetic anisotropy parameters deduced from magnetic resonance allows for a good fit of the angular variation of the normalized static remanence coefficient [Fig. 3(a)] as well as for the in-plane field dependence of the frequency [Fig. 3(c)]. For the remanence, the calculation is based on the coherent rotation model. Its variation only depends on φ_u, φ_6 and H_u/H_6. It is to notice that H_u/H_6 is not small enough to significantly shift the direction of the zero-field magnetization away from φ_u: it results that the calculated angle for the minimum of M_r/M_s practically corresponds to the direction normal to $\boldsymbol{H_u}$ [in the example illustrated in Fig. 3(a), M_r/M_s vanishes for an angle of 7°, to compare to the 11° value defining the hard axis related to H_u].

IV. CONCLUSION

The static and dynamic magnetic properties of 6, 10 and 31 nm-thick $Fe_{1.7}Ge$ films, deposited on Ge(111) substrates have been studied. Our X-rays diffraction measurements show an excellent epitaxial growth with an hexagonal $B8_2$ structure. The (111) substrate cubic axis coincides with the (0001) hexagonal axis of the $Fe_{1.7}Ge$ film. The magnetic behavior is interpreted assuming a magnetic energy density in which the contribution of the in-plane anisotropy consists in two distinct terms showing a twofold and a sixfold symmetry, respectively. The studied samples present very similar structural and magnetic characteristics. The sixfold anisotropy field increases with the thickness while the in-plane uniaxial anisotropy field seems to depend on the elaboration conditions. A good agreement is observed between the parameters extracted from MS-FMR and from TBIIST measurements.

[1]H. Ohno, A. Shen, F. Matsukura, A. Oiwa, A. Endo, S. Katsumoto, and Y. Iye, Appl. Phys. Lett. **69**, 363 (1996).
[2]T. Jungwirth, K. Y. Wang, J. Mašek, K. W. Edmonds, J. König, J. Sinova, M. Polini, N. A. Goncharuk, A. H. MacDonald, M. Sawicki, R. P. Campion, L. X. Zhao, C. T. Foxon, and B. L. Gallagher, Phys. Rev. B **72**, 165204 (2005).
[3]R. Jaafar, Y. Nehme, D. Berling, J. L. Bubendorff, A. Mehdaoui, C. Pirri, G. Garreau, and C. Uhlaq-Bouillet, Appl. Phys. Lett. **93**, 033114 (2008).
[4]R. Jaafar, D. Berling, D. Sébilleau, and G. Garr, Phys. Rev. B **81**, 155423 (2010).
[5]B. Malaman, J. Steinmetz, and B. Roques, J. Less-Common Met. **75**, 155 (1980).
[6]D. Berling, S. Zabrocki, R. Stephan, G. Garreau, J. L. Bubendorff, A. Mehdaoui, P. Wetzel, D. Bolmont, C. Pirri, and G. Gewinner, J. Magn. Magn. Mater **297**, 118 (2006).
[7]M. Belmeguenai, F. Zighem, Y. Roussigné, S.-M. Chérif, P. Moch, K. Westerholt, G. Woltersdorf, and G. Bayreuther Phys. Rev. B **79**, 024419 (2009).